PB82-185182

Considerations of Environmental Protection Criteria for Radioactive Waste

(U.S.) Office of Radiation Programs
Washington, DC

Feb 78

U.S. Department of Commerce
National Technical Information Service
NTIS.

PB82-185182

Background Report

Considerations of Environmental Protection Criteria for Radioactive Waste

February 1978

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Radiation Programs
Waste Environmental Standards Program
Washington, D.C. 20460

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

Reproduced from best available copy.

[6560-01]

ENVIRONMENTAL PROTECTION AGENCY

[FRL 843-1]

ENVIRONMENTAL PROTECTION CRITERIA FOR RADIOACTIVE WASTES

Announcement of Public Forum

AGENCY: Environmental Protection Agency.

ACTION: Announcement of Public Forum.

SUMMARY: The Environmental Protection Agency (EPA) will hold a Public Forum on Environmental Protection Criteria for Radioactive Wastes at the Stouffer's Denver Inn, Denver, Colo., March 30 to April 1, 1978. The purpose is to provide for extensive public review of a background report, available February 1, which includes the Office of Radiation Programs' initial formulation of proposed guidance for all types of radioactive wastes.

FOR FURTHER INFORMATION CONTACT:

Project Leader for Environmental Criteria, Waste Environmental Standards Program (AW-460), Environmental Protection Agency, 401 M Street SW., Washington, D.C. 20460, telephone 703-557-8927.

SUPPLEMENTARY INFORMATION: Notice has been given (41 FR 53363) that EPA intends to develop environmental radiation protection standards for high-level radioactive waste to assure protection of the public health and the general environment. This development will focus initially on two major outputs: General environmental protection criteria for all radioactive wastes, which are the subject of the Forum announced here, and numerical standards for high-level radioactive waste. These criteria and standards will be developed under the broad authorities transferred to the Agency from the former Atomic Energy Commission and the former Federal Radiation Council by Reorganization Plan No. 3 of of 1970.

Prior to developing its initial formulation of proposed guidance, the Agency has sought broad public input through two open workshops: at Reston, Va., on February 3-5, 1977, and at Albuquerque, N. Mex., on April 12-14, 1977. The purposes were to define key terms related to the radioactive waste problem, and to examine basic concepts concerning both the risks associated with wastes and the long term implications of their management, including disposal. Participants were free to advise EPA on any matter they consider appropriate.

EPA has now developed an initial formulation of proposed guidance for radioactive waste storage and disposal, using the inputs received from these workships to the extent feasible. Before finalizing this formulation into formal proposed guidance, the Agency feels it is desirable to have further public review and discussion, since many of the concepts involve new precedents in radiation protection. The initial formulation will be the basis for discussion at the Forum, and will be available as a source document by February 1, 1978.

The Forum will take place in Denver, Colo., at the Stouffer's Denver Inn on March 30 to April 1, 1978. Following brief presentations by EPA staff on how and why its recommendations were developed, working groups will be set up according to the topics the background report covers. Participants will be expected to direct their attention specifically to EPA's initial formulation of proposed guidance and to develop comments accordingly, rather than to explore the issues in general.

The Forum is free, but, to assist EPA in planning sufficient meeting arrangements, people who wish to participate are asked to pre-register with the Manager, EPA Workshop, Ecological Analysts, 257 Broad Hollow Road, Melville, N.Y. 11746. Anyone who attended either of the two previous workshops will automatically receive an invitation and a copy of the background document containing the Agency's initial formulation of proposed guidance. Those who would like to provide written comments instead of attending the Forum may request the same information from EPA at the above address. All comments received by either process will be considered in preparing the criteria for formal proposal in the FEDERAL REGISTER.

Dated: January 8, 1978.

DAVID HAWKINS,
Assistant Administrator for Air and Waste Management.

[FR Doc. 78-1176 Filed 1-13-78; 8:45 am]

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
		PB82 185182

4. TITLE AND SUBTITLE	5. REPORT DATE
Considerations of Environmental Protection Criteria for Radioactive Waste	February 1978
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Environmental Protection Agency Office of Radiation Programs ANR-460 Washington, D.C.	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Same as above	13. TYPE OF REPORT AND PERIOD COVERED Background Report
	14. SPONSORING AGENCY CODE 200/03

15. SUPPLEMENTARY NOTES

Reproduced from best available copy.

16. ABSTRACT

Although most waste materials contain some radioactivity, their designation as radioactive waste in dependent on their having no perceived value, their origin, and whether the materials pose undesirable exposure circumstances. This document develops the considerations for and initial formulations of environmental protection criteria for radioactive wastes.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Radioactivity Waste		

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release unlimited	unclassified	
	20. SECURITY CLASS *(This page)*	22. PRICE
	unclassified	

BACKGROUND REPORT

CONSIDERATIONS OF ENVIRONMENTAL PROTECTION CRITERIA FOR RADIOACTIVE WASTE

Waste Environmental Standards Program
Office of Radiation Programs
U.S. Environmental Protection Agency
Washington, D.C. 20460

February 1978

PREFACE

When EPA was formed in 1970, one of its charges was to "advise the President with respect to radiation matters, directly or indirectly affecting health, including guidance for Federal agencies in the formulation of radiation standards..." This responsibility includes protection of the public health from potential hazards associated with the various forms of radioactive waste.

This Background Report develops considerations for and initial formulations of environmental protection criteria for radioactive wastes, and as such, will provide the basis for additional public participation in developing the criteria. In this regard, public input was received from two public workshops held by EPA in February and April 1977 to address relevant policy and technical issues. A third public forum of similar format is planned in the spring of 1978 to discuss this Background Report and its initial formulations. The public is invited to further assist the Agency by attending this forum or by providing written comments, which will be considered and responded to before formally proposing the criteria. Both the scope and details of the initial forumulations are subject to change to accommodate these comments.

The Agency has also begun the technical environmental impact assessments needed to develop a standard specifically directed at high-level, long-lived radioactive wastes. The standard will be in accordance with the criteria, and it will be the first of a series of environmental standards for major classes of radioactive wastes.

James E. Martin, Ph.D.
Manager, Waste Environmental Standards Program

CONTENTS

Introduction 1
Radioactive Wastes and Hazards 3
Risk Considerations for Radioactive Wastes 14
Control of Radioactive Waste 22
Risk Perspectives 30
Other Considerations for Radioactive Waste 43
Summary and Recommendations 47
Glossary 54
Appendix A 56

INTRODUCTION

The responsibility of present generations to maintain environmental quality for future generations is well recognized. As enunciated in the National Environmental Policy Act of 1969, it is an important national goal to "fulfill the responsibilities of each generation as trustee of the environment for succeeding generations." Many radioactive waste materials are both long-lived and highly radioactive, and therefore could represent substantial risk that could be transferred from present generations to future ones. Because of this potential risk not only to present generations but to future ones as well, it is important that such materials be properly controlled.

It is generally conceded that risk estimates for many of the long-lived radionuclides would depend on numerous imprecise variables which would be little more than speculation after certain time periods. For example, C-14, Pu-239 and I-129 could present potential dose commitments for hundreds of thousands to millions of years. Such uncertainty could result in intense controversy over any calculations or judgments upon which environmental protection criteria or standards would be based. This circumstance places a considerable burden on government decisions regarding radioactive wastes. These decisions should recognize the public's perception of the problem; however, to date there seems to be little public concensus concerning appropriate management of radioactive wastes.

Development of environmental protection requirements for radioactive wastes basically involves: 1) features of radioactive materials that require them to be designated as radioactive wastes and

their hazard potential over time and at various levels of controls, 2) the importance of risk estimates in arriving at levels of control and the factors that should be reflected in such determinations, 3) the goals of control and the types of institutional, engineered, and natural-barrier controls for meeting such goals, 4) the approacnes for determining the allowable levels of short- and long-term risks associated with various means of disposal for types of waste materials, and 5) other considerations for environmental protection such as retrievability, monitoring, and transfer of information to succeeding generations. This Background Report addresses these five areas in sequence in order to make recommendations for environmental protection criteria which are to be used in the development of environmental standards for major classes of radioactive waste.

The Agency held two workshops in 1977 to gather a variety of views on major issues, and has given careful consideration to the views expressed there in drafting this document and the initial formulations of environmental criteria. The major findings of the workshops are summarized in Appendix A and referred to in this document where they apply.

RADIOACTIVE WASTES AND HAZARDS

Radioactive Wastes

Radioactive wastes are a consequence of the use of either human-produced or naturally-occurring radioactive materials. These wastes are produced in a broad range of forms, concentrations, and quantities. They may be gaseous, liquid, or solid in form, may be soluble or insoluble in water, and may emit several types of radiation over a wide range of energy and rate. The concentration of wastes varies from highly radioactive spent reactor fuel wastes and disused radium sources to very low natural radioactivity in residues from certain mineral processing activities. Between these extremes is a broad range of wastes of varying radioactivity resulting from medical, industrial, and scientific radioisotope applications. The two extremes generally encompass the range of sources, potential hazards, and inventories of radionuclides that need to be considered in establishing environmental protection criteria for the disposal of materials containing them.

In order to designate a material as radioactive waste, it should be first declared a waste, that is, it has no anticipated use or value. Since virtually everything in use contains some measure of radioactivity, a drastic narrowing is obviously required to decide which materials should be designated as radioactive wastes Almost any waste would be included if the only required characteristics were that a material be radioactive and have no future use. As a starting point, it seems clear that radioactive wastes should include materials restricted by regulatory controls from discharge to the general environment.

Recognizing that most substances contain some natural radioactivity, it is necessary to differentiate when they should be considered radioactive wastes rather than assuming they are just wastes with no need to consider their radioactivity content in disposing of them. Such waste materials could be reasonably classified as being non-radioactive wastes if nothing is done to make the radioactivity content more accessible for exposure of humans than would normally exist due to natural conditions. Using the same consideration, if disposal of these materials in the environment would not increase the pre-existing exposure level to humans via any pathway at the site, they should not require special care due to their radioactivity. It also seems reasonable that the location of a disposal site should not be chosen just to be able to dispose of material with high natural radioactivity concentration without consideration of the fact that the radioactivity has been made more available for human exposure. For example, shipping Florida phosphate tailings to a high background area for disposal would not be justified even if it were feasible.

Many artifically-produced radioactive materials, such as those produced by nuclear fission or activation, are subject to regulatory controls to avoid unjustified exposure of the public by discharge to environmental pathways or other means. Such materials are by mode of production under human control and thus the perspective for their designation as radioactive wastes and required care is somewhat different from naturally-occurring diffuse radioactive materials. Any waste material that is restricted from discharge to the general environment should be considered radioactive waste and subjected to

environmental protection requirements when being managed or disposed of; this condition is especially applicable to retained human-produced materials such as fission products from fuel reprocessing, or liquid or gaseous wastes removed from effluent streams to meet environmental requirements. It is also reasonable to apply the same condition to naturally radioactive materials removed from effluents because of discharge restrictions.

The designation of radioactive wastes and the controls they receive is influenced by the potential for individuals and populations to be exposed to them and the timeframe over which they persist as radiological hazards. If any waste material containing human-produced radionuclides were reasonably controllable to reduce potential human exposure, then this would also be a justifiable basis for designating it as a radioactive waste.

Types and Hazards of Radioactive Wastes

The sources, potential hazards, and inventories of radioactive wastes are represented by: 1) radioactive materials either artificially produced or fabricated from natural materials such as radium into discrete sources, and 2) diffuse naturally-occurring radionuclides such as the by-products of mining and milling operations. Radioactive wastes in the first group are deliberately produced or assembled. They vary greatly in activity, form, volume, and radiological hazard implications, and consist primarily of high-level, low-level, and transuranic contaminated wastes. Other sources of this nature are naturally-occurring nuclides concentrated in discrete sources such as Ra-226 needles used in medical therapy.

Materials in the second group are not institutionally produced, but are rearranged as a result of human activities such as the redistribution of naturally-occurring radioactive materials due to mining and milling of ore bodies. The majority of these wastes are associated with mining and milling operations; uranium tailings and residues of phosphate mining are prime examples of these wastes.

"High-Level Waste" traditionally refers only to the liquid stream resulting from reprocessing of spent reactor fuel, and to any solidified derivatives of that liquid. Because other materials present hazardous levels of risk, "high-level wastes" as used here will also include all forms of radioactive wastes which have the capability to produce radiation exposures with acute effects. The major source of such wastes is currently nuclear fission reactors resulting in either spent fuel, or the products of reprocessing the fuel.

High-level wastes containing fission products emit penetrating gamma radiation, which means that mere proximity to the material may be hazardous. Also, most quantities of such wastes produce sufficient heat from radioactive decay to increase the potential for uncontrolled release to the environment. Following such a release, dilution would reduce the direct radiation hazard so that inhalation and ingestion hazards would then predominate. These pathways to people arise from volatilization, particulate dispersion, and dissolution of the waste. The actual hazard would vary with the isotopic composition of the material. In the case of the waste from reprocessed nuclear fuels, for example, Sr-90 and Cs-137 would be the controlling inhalation hazard,

and Sr-90 would be the controlling ingestion hazard for the first few hundred years after the material is produced.

The total inventory of high-level fission product waste at Federal sites is about 76 million gallons with an activity of about 400 million curies (JCAE, 1975). It has been estimated that these wastes will continue to accumulate at a rate of about 300 thousand gallons per year. Since most of the spent fuel from commercially operated reactors has not been reprocessed, the resulting high-level liquid waste is currently only 0.6 million gallons, which contains approximately 310 million curies (NRC, 1976; EPRI, 1976). The remaining unprocessed spent fuel elements from commercial nuclear power plants are in temporary storage, pending a decision on future disposition. It has been estimated that spent fuel elements in storage as of 1975 corresponded to 1365 metric tons of uranium (ERDA, 1976). If reprocessing becomes an element of the commercial nuclear fuel cycle, it is estimated that each metric ton of fuel processed would result in 400 gallons of high-level liquid wastes (Cohen, 1972). It should be noted, however, that the expected total amount of liquid may not exist at any one time if the current regulations requiring solidification after five years remain in effect.

Other high-level wastes include certain discarded sources used in medicine and industry such as Co-60, Cs-137, Sr-90, etc. High-level sources such as Ir-192 are also used for industrial applications such as nondestructive testing. The current inventories and annual production rates of high-level wastes from medical and industrial applications are difficult to estimate, but it is expected that the amounts of wastes containing such sources would increase.

"Low-Level Waste" has generally been used to include substances not readily classified otherwise; therefore, the term has covered material with a very broad range of origins, physical and chemical forms, radioactive lifetimes, and radiological hazards. For present purposes, low-level wastes include materials which would not present an acute hazard (induction of radiation sickness over a relatively short period of time) to maximally exposed individuals. In applying this principle, certain wastes usually designated as low-level, such as some reactor wastes and discrete medical and industrial sources, may no longer fit this classification. A potential hazard to the public from low-level wastes is radiation exposure via water that may come into contact with the waste material and leach various radionuclides into solution. These may eventually be ingested by humans through their food, milk, and drinking water. The resulting exposure depends upon the rate of transfer of the radionuclides through the surrounding soil and groundwater, the amount of dilution or concentration that occurs, and other factors. Radioactive dust may result from poor handling of materials during disposal operations, and subsequent inhalation of the dust could pose a serious health hazard.

Through 1976, the commercial sector generated 15 million cubic feet of waste packages containing 3.8 million curies of low-level waste (Holcomb, 1977). It has been estimated that in 1974 Government sites contained 17 million curies in 42 million cubic feet of packaged waste (GAO, 1976; NAS, 1976). Wastes from the commercial sector are being generated at a rate of approximately 2 million cubic feet per year, and are increasing each year (O'Connell, 1974). Production of low-level

wastes from Government programs is stable at approximately 1.3 million cubic feet per year (AEC, 1975; Wong, 1973).

Long-Lived Wastes are especially significant because their persistence represents continued risk to humans far into the future even in small amounts. Transuranic (TRU) contaminated wastes (isotopes with atomic number greater than 92, e.g. Np, Pu, Am) are especially significant because they have long half-lives and some are highly radiotoxic. TRU's are primarily produced by single or multiple neutron capture by U-238 in fuel elements during the operation of a nuclear reactor. Reprocessing of spent fuel elements removes plutonium, but since the separation is not complete, the resulting high-level liquids still contain some plutonium (less than about 0.5 percent) as well as other transuranic material. Likewise, transuranic contamination of low-level wastes also occurs when the transuranic materials are handled or processed, which is primarily at Government facilities involved in nuclear weapons production.

Transuranic wastes are persistent in the environment, but as a general rule, are strongly retained by soils. They are not easily transported through most food chains, although some concentration does take place in the aquatic food chain. They pose only a slight biological hazard to humans upon ingestion because absorption through the gastrointestinal tract is slight. A greater potential hazard results from inhalation of dust particles containing TRU materials because a significant fraction would be retained in the lung or be absorbed into other tissue. The potential to produce adverse health effects depends upon the particle size and solubility of the inhaled

material. Upon entry into the bloodstream (either by ingestion or inhalation), TRU wastes readily accumulate in bone and liver tissues and can significantly increase the risk of cancer.

Prior to 1970, TRU-contaminated wastes were not segregated from other low-level wastes. At sites used by the Federal Government for its own wastes, materials are not placed in the site if they contain greater than 10 nanocuries of alpha-emitting radionuclides per gram. About one million cubic feet containing some 215 thousand grams of TRU wastes are currently in storage at Federal sites. Such wastes are accumulating at a rate of about 400 thousand cubic feet per year (NAS, 1976). Five of the six operating commercial burial grounds currently exclude wastes containing greater than 10 nanocuries of transuranic radionuclides per gram.

Other long-lived radionuclides which may be of special concern are I-129 and C-14. Iodine-129 is a volatile nuclide with a half-life of seventeen million years; thus, its isolation from the biosphere over the long term will be difficult to assure. Carbon-14 has a half-life of 5600 years and, if released to the biosphere, would represent exposure of the entire world's population due to rapid movement into the carbon cycle.

Fabricated Naturally Radioactive Wastes are discrete sources such as radium needles and radon seed implants commonly used for therapeutic medical purposes. Other such sources are neutron sources fabricated from beryllium and polonium or radium which are used in industrial drilling applications. Wastes resulting from these uses range from high-level to low-level and the radiological hazards vary accordingly.

The radiological hazard from a Ra-226 source, for instance, is largely due to external gamma irradiation or, when inhaled or ingested, to internal alpha emission. Because the hazards from discrete sources of naturally-occurring nuclides vary so greatly, they need to be determined on a case-by-case basis. Inventories of these sources are estimated to be small.

Diffuse Wastes of Naturally-Occurring Radionuclides exist, which, by virtue of their natural origin and the methods of production, are dispersed through a bulky nonradioactive matrix. Common examples are uranium mill tailings and phosphate mining and processing wastes. Similar wastes, though of much lower radioactivity concentration, result from activities such as copper mining and coal combustion. These wastes contain the naturally-occurring radioisotopes of uranium, thorium, radium and other uranium daughter products.

Diffuse wastes represent chronic rather than acute exposure. The primary pathway to humans for such exposure is the inhalation of radon and its daughters. This results in radionuclide deposition in the lung, skeleton, and liver. Past experience indicates that radon gas produced by radium decay migrates into residential structures built on or near uncontrolled waste and tailings piles. In a number of instances, as observed with uranium mill tailings in Grand Junction, Colorado, and reclaimed phosphate mining land in Florida, elevated levels of radon daughters were measurable in structures, although in numerous cases the total radium source term was relatively low (EPA, 1976a). This indicates that radium levels in diffuse waste could present a potential hazard and still not greatly exceed background levels.

Compounding this waste management problem is the longevity of the radionuclides involved. Thorium-230, the parent nuclide of radium-226, has a physical half-life of about 80 thousand years, which can be considered the effective half-life of the radon exposure hazard. The persistence of this waste makes it impossible to control public access to it by any institutional means. The current practice of stabilizing the tailings by cover has been only a temporary solution of limited value due to the ability of radon to diffuse through most natural media. The very large quantities of waste involved, the variability of natural background radium concentrations, and the cost and availability of control technologies are important considerations in determining management of these materials.

By far the largest quantities of naturally-occurring, diffuse radioactive wastes are the solid residues from mining and milling of uranium and phosphates. These include the overburden and excavated materials from open pit and underground mining, and the tailings from milling operations. Tailings contain about 99 percent of the original ore mass, and more than 97 percent of the uranium series radioactive decay products. The accumulated volume of uranium tailings through 1976 is assumed to be equal to the total volume of mined ore, which is thought to be near 138 million tons. Approximately 23 million tons of tailings are located at inactive mill sites and the remaining 115 million tons are at operating sites (Hendricks, 1977). The total radioactivity of the mill tailings is estimated at 140 thousand curies (EPA, 1977a). There are some 300 million tons of phosphate mill tailings containing approximately 10,000 curies of Ra-226 (EPA, 1977b).

Radioactive Waste Materials

Application of the factors and considerations above leads to a conclusion that radioactive material which has no foreseen value would be radioactive waste if it contains artificially produced radionuclides, contains naturally-occurring radionuclides in such concentrations that release to the general environment would increase exposure to humans above that normally occurring in pathways due to the natural state of the area, or contains either type of material which is restricted by regulations from routine release to the general environment. Examples of such materials that would be radioactive wastes subject to environmental protection criteria in determining their storage and disposal are:

- All radioactive materials associated with the operation of nuclear reactors for either military or other purposes and the supporting fuel cycles including spent fuel, fuel reprocessing wastes, and radionuclides removed from effluents.
- Artificially produced radioisotopes for medical, industrial, and research use, including discrete radium sources, and waste materials contaminated with them.
- The naturally radioactive residues of uranium and phosphate ore recovery and associated milling and conversion operations.

RISK CONSIDERATIONS FOR RADIOACTIVE WASTES

Radioactive wastes represent a risk of potential exposure to people which varies considerably with time. The risks are dependent to a large extent on whether the wastes are controlled, the type of controls that could be adopted, and how long the controls would last. In a practical sense, risk considerations and control considerations are necessarily interrelated because each influences the other. Therefore the risks due to the presence of radioactive wastes in the human environment need to be assessed without controls and at different levels of control. The risk assessed at a particular level of control is especially important to the consideration of whether a risk is acceptable, which is discussed further in a later section.

Technical, Economic, and Social Considerations

It should be noted in this regard that there is no way to guarantee absolute protection from pollutants such as radioactive materials, which are assumed to have no threshold for effects, other than by prohibiting their production. In order to receive the benefits of an activity in which radioactive wastes are produced, regulatory and advisory bodies have considered the costs of achieving a given level of health and environmental protection. Provided that basic health and social objectives are being satisfied, it has long been the practice in radiation protection to apply additional controls until further expenditures are no longer justified because of the minimal improvements in health protection.

A significant issue is whether the possibility of exposure to radiation from waste can be justified at all, in view of the universal understanding that waste itself is a material which is not being used for any beneficial purpose. This issue is somewhat different, however, if one is trying to reach conclusions about existing wastes as opposed to wastes which have not yet been produced. For existing waste, the only possible justification for accepting any risk other than zero is that the expenditure and commitment of resources required to eliminate all chance of exposure to humans, if that should be possible, may not be warranted by the increase in safety that would thereby be achieved. The only policy issue for existing waste, therefore, is whether at any given level of control the expenditures or other costs to gain additional control are justified by the degree of risk reduction that would result.

For wastes which have not yet been produced, it is logical to view the requirements for safe management of any radioactive wastes as part of the economic, social, and health and environmental costs of achieving the desired product. Justification for any risks permitted due to the wastes must be found in the beneficial aspects of the enterprise, which should exceed the costs. Analyzing and comparing these total costs and benefits for a complex enterprise is well known to be profoundly difficult (see for example, BEIR II, 1977). However, in cases where any risks associated with radioactive wastes could be avoided by not producing the waste, justification for assuming the risk would be related to the net value of the productive enterprise.

A wide range of viewpoints exists over the nature of the responsibility of the waste producers to provide protection for future

populations. Such a range was observed at the EPA workshops. It is argued by some that because only the waste producers receive the benefits associated with the production activities, future people should not be subjected to any burden at all because they had no role in the decision-making process. A divergent view is that future societies are indeed beneficiaries of the technological activities which produce the waste, and therefore it is not unfair for them to share some portion of any potential risks. Moreover, if future poeple were more technologically advanced, they would be more able to provide for their own protection than are the waste producers. On the other hand, if less technologically advanced, the potential consequences to any amount of exposure may well be less than already assumed. A caution is necessary, however, in that a decision not to take action to mitigate a problem may place economic burdens on future generations. An example of this circumstance is evidenced by existing uranium tailings piles which were originally placed in their current location at a fraction of today's costs, but would be quite expensive to relocate.

Many variations and elaborations of these views have been expressed. However, one of the clearest conclusions to emerge from the discussions at the EPA workshops was that limitation of the long-term risk should be an important element of environmental protection criteria for radioactive wastes. Similarly, a study of public attitudes and values associated with radioactive waste disposal based on polling techniques showed that long-term safety is widely held to be at least as important as safety over the short term (Maynard, 1976). Protection of future populations from the potential hazards of radioactive waste

indeed should be a primary objective of waste storage and disposal programs. Any potential risks should also be no greater than those acceptable to the producers, and preferably should be less in view of the unavoidably greater uncertainties in risk estimation for the long-term.

Risk Determination

The potential to produce adverse health effects is directly related to the total amount of a given radioactive material in a location, the relative concentration of radionuclides in the waste, their availability for exposure, and their respective radiotoxicities. Also, the timeframe for concern with radioactive wastes is determined by the half-lives of the various radionuclides; thus their availability is dependent upon the time they are contained. These exposure-temporal relationships and the mode of control establish whether potential effects are acute (promptly observable physical changes) or chronic (potential increase in cancer rate, genetic disorders, etc.) and whether they occur over short or long periods or both. Each of these is important to decisions on the degree of control imposed for any radioactive waste; thus, an estimate of the type and amount of exposure over time is basic to risk determination for radioactive wastes.

The degree of risk that the producing generation passes on to the future represents an important legacy of radioactive wastes. This transference involves a moral judgment of responsibility, including the length of time for which responsibility extends into the future. An ethical basis for decisions regarding risk transference is needed not only for philosophical reasons, but also for the practical purpose of

implementing evaluation techniques such as cost-effectiveness and risk-cost analyses. Unfortunately, society has not established clear approaches for dealing with the imposition of such risks far into the future.

Once it is accepted that the waste producing society is responsible to provide environmental protection and limitation of risk for future populations, it still remains to be decided how far into the future responsibility should extend. The implications of such a decision are not purely philosophical, however. One of the bases upon which alternate waste storage and disposal systems would be compared, and with respect to which judgments of acceptability of technology will be made, is their associated risks. The farther into the future the responsibility extends the greater will be the number of people to be protected, and, it may be supposed, the greater the justification for additional measures of control.

For long-lived radioactive materials such as I-129, environmental impact calculations may be estimated over indeterminately long times. Although there is certainly a need to evaluate the long-term impacts of waste storage and disposal decisions, there are serious and intrinsic practical limitations to the performance of such evaluations. Assumptions regarding population sizes, future food and water supplies, and the effectiveness of medical interventions become purely speculative when performed for periods of thousands to millions of years, and therefore provide little, if any, basis for waste disposal evaluations.

These circumstances argue for some practical time interval upon which to base health effect estimates to future people during which some

meaningful representation of the potential health risk may be achieved. Selection of this time interval is, of course, arbitrary, but two authors (Schiager, 1977 and Rochlin, 1977a) who have examined the question have suggested that future social conditions beyond a few hundred years were not sufficiently predictable to be relied upon. However, because of the long term duration of the potential risk involved, it appears reasonable to use a conservative approach and stretch to its outer limits the period of time during which extrapolation of current trends and expectations may make some sense. Population trend estimates break down after a few hundred years, but the physical parameters of source terms, environmental transport models, and geological parameters may be reasonably predictable for a few thousand years. A good balance between these would suggest that about 1,000 years is a reasonable time for such estimates.

Risk estimates performed for more than 1,000 years would probably not influence the degree to which available waste management systems would be required, even if improvements in basic scientific knowledge were to reduce the inherent uncertainties after a thousand years or so. Some general cases may be exceptional such as transport of some transuranics, I-129, or C-14, and general estimates of long-term effects on the environment and public health beyond 1,000 years may be reasonable for an assumed population and release time. In such circumstances it would be useful for risk estimates to be extended beyond 1,000 years to gain general understanding of the potential risk, especially if these determinations could influence the type of control chosen. Also, long-term estimates may be reasonably important in

justifying the production of new wastes containing long-lived nuclides such as I-129.

Consideration of controls, how they are used, and how they perform with time is also essential to risk estimations. It is especially important that the timeframe over which particular radioactive waste materials remain hazardous be considered from two basic standpoints, the performance of the control alternatives in reducing the risks over time and the probability of any containment being breached. A range of controls exists that are either institutionally based, technologically imposed, or dependent on natural barriers such as geological media to provide public health protection. These can also be used in combination depending on the circumstances and whether imposing multiple barriers would reduce the probability of potential impacts. The performance level of such controls and the probability of their failure should also be included in risk determinations. Even if wastes are of such persistence that they can be assumed to eventually get back to the environment, the reduction of collective dose over the period of successful containment is very desirable.

Role of Risk Determination in Criteria

The factors discussed above make risk determination a pivotal part of any environmental and public health protection policy for radioactive wastes. This leads to the general conclusion that the key consideration in deciding whether and how to store or dispose of radioactive wastes should be based primarily on an assessment of the risk for a wide range of relevant factors, especially the level of potential exposure, the time involved, and levels of control. Because of the long term

implications of many of the waste materials and the ethical responsibility to minimize intergenerational risk transference, it is concluded that as a limiting case the risks imposed on future generations be no greater than those the producing generation is willing to accept, as expressed in the public health protection standards and policies it adopts.

Risk determinations rest on a number of key factors, especially the total amount of waste material in a location, its persistence due to form and concentration, the potential to enter the biosphere and produce adverse health effects on individuals and populations, the effectiveness of various controls imposed, and the inherent uncertainty of many of the parameters. Risk determinations which address these factors should be performed for at least 1000 years. General estimations for longer periods are also appropriate for very long-lived materials where this consideration would be an important aspect in determining the proper disposal option for existing wastes or justifying the production of new wastes.

CONTROL OF RADIOACTIVE WASTE

Avoidance of potential exposure of individuals or populations due to radioactive waste depends on the control methodology used to isolate the material and whether the period over which control is assured is long enough for the radiological hazards to decrease to an acceptable level. In this respect, the ultimate goal of radioactive waste management is total isolation of wastes from the biosphere to the degree that this is achievable considering technical, economic, and social factors. Control of the potential impact on humans is essential; however, it is not in itself a totally sufficient condition because of the trustee responsibility each generation has to succeeding ones. For this reason, it is also necessary to prevent any unnecessary contamination of the environment which is reasonably achievable even though human interactions with the wastes could not be presently predicted. From these considerations, the goal for control of radioactive wastes should be to prevent its introduction into the biosphere over its hazardous lifetime.

Control of radioactive wastes can be provided by institutional forms of management or by disposal. Institutional management is used primarily to control exposure to present populations and includes the acquisition, treatment, preparation, and storage of radioactive wastes. The disposal of radioactive wastes, on the other hand, presumes no such dependence on formal institutional mechanisms to maintain isolation of the wastes from the biosphere. Rather, disposal is achieved by placing the wastes in an acceptable location with no intent of recovery. In

general, institutional management of radioactive wastes is a short term process; disposal is a long term action.

With respect to ultimate disposal, which generally would depend on environmental barriers, proper site selection is important to maintaining protection of the materials over the period of time a radiological hazard exists. In this respect, it is desirable for sites to provide stable isolation over time; thus, the action over time of natural forces, such as erosion, sedimentation, and crystallization ideally should be projected to improve environmental isolation rather than reduce it. For example, wind may be expected to erode the covering of an elevated shallow land burial site, but if the location of such a site were carefully chosen, the action of wind might be expected to increase earth cover with time. All other things being about the same, this latter situation would be more desirable.

Isolation of waste materials is an important consideration for reducing their risk-producing potential. For waste materials of low or short term risk potential, temporary isolation may be satisfactory. For materials which represent long term risk, the ideal goal would be permanent isolation over the hazardous lifetime of the radionuclides with the probability of breaching the containment or intrusion being very low. In general, permanent isolation cannot be expected; therefore, isolation by some form of optimized containment is usually selected based on a balance between uncertain future risks and more certain near-term risks. An example of optimized containment would be the disposal of uranium mill tailings where, even though the half-life of the material would make permanent isolation desirable, it is not

practicable because of the large volumes of the materials involved. Optimal containment for such wastes may require a compromise between practically providing earth cover to reduce radon emissions and recognition that a finite probability of intentional or accidental intrusion could still exist.

Institutional Controls

It is reasonable to rely on institutional mechanisms to provide control of radioactive waste for the immediate future. However, some of the materials will remain potentially hazardous for time periods well in excess of the several years to decades for which societies routinely lay and execute plans. The question arises: for how long into the future should decision-makers plan to rely on institutional controls as a substantial means of protecting the environment and public health from today's radioactive waste?

As an initial step in examining this issue it is illuminating to compare the longevities of radioactive waste and institutional structures. Three general time scales for such comparisons have been suggested (Schiager, 1977):

1. Human lifespans - the industrial-technological experience of human society, as well as human life itself, occurs on a time scale on the order of a few decades. Within this period there may be some validity to technological, economic, or sociological projections. Projections for the more distant future, however, become increasingly uncertain and dependent upon broader assumptions of socio-economic conditions.

2. Political lifespans - time scale based on the recorded history of civilizations and political entities would be on the order of centuries to millenia. From such a perspective, though, it is clear that the preservation of materials or structures from past civilizations has been in spite of, not because of, political activities. Dependence on political stability with regard to institutional longevity would therefore be questionable.

3. Geologic time - on the order of millions of years, the basis for this scale is natural forces, and not social or technological assumptions. Although the time scale is great, extrapolations to the future on this basis may be valid because of the relative predictability of such forces.

In another analysis of the temporal question, however, it has been suggested that a distinction between phases of institutional control can be made solely on the basis of predictive reliability. Three time periods have been proposed within this framework (Rochlin, 1977b):

1. Short term - less than 50 years. It is postulated that over this period of time, reasonably sure predictions can be made about the stability, goals, and operation of human institutions, as well as the degree of uncertainty in making these projections.

2. Intermediate term - one to two hundred years. Predictions for such time periods, based largely on extrapolation or projection of present trends, can be made with some limited degree of confidence. It is recognized, however, that the

cumulative error resulting from new circumstances and unforeseen developments over such periods can result in radical structural and policy changes. The degree of uncertainty in projection, therefore, increases sharply during this period.

3. Long term - greater than one to two hundred years. Uncertainties dominate predictive ability. For more than a few thousand years, there is only uncertainty.

Deciding on a reasonable time for dependency on institutional controls is essentially equivalent to estimating the shortest likely period of institutional continuity. It is clear that there is no definitive scientific method for such a determination, but it is difficult to predict the course of events from current trends for more than several hundred years. The cumulative effect of future events and developments may result in unforeseen radical changes in social structures and policies. For example, the depletion of certain resources (petroleum, for example) may adversly impact society and the stability of its institutions in just a few decades. Although it may be argued that there are numerous examples of public and private institutions which have functioned for periods of much more than several hundreds of years, there is little basis for presuming that a given current social organization will survive for a like period of time or that it will be aware of or have concern for radioactive wastes. The distinction is one of perspective; historical citations are certain, while predictions are not. The wastes in question are not only useless but will often be in remote locations and some may be hazardous only in

the sense of chronic exposure. Therefore, some radioactive wastes may be easily forgotten following social discontinuities.

Clearly, institutional means of controlling radioactive wastes should be used as supplements to other methods for as long as they are effective and efficient. In view of the matters discussed above, however, it does not appear to be prudent to plan waste storage and disposal systems in which basic elements of safety rely on the performance of human functions for more than about 100 years. This is not to suggest that society or its institutions would not be expected to exist beyond 100 years, only that those institutional activities such as maintaining a controlled site boundary could not be relied upon to protect wastes which have no artistic or other value that would make future people want to continue to give them special care. A better approach is warranted. The planned institutional phase could be still shorter, of course, to allow a greater margin for error, but 100 years of institutional continuity appears from a historical perspective to be reasonabe. Alternate time periods could also be chosen depending on the degree of reliance one is willing to place on technical, economic, and social considerations.

Environmental Controls

Environmental controls are mainly represented by geological media with physical properties that inhibit the movement of radioactive waste. In general, they are used in conjunction with engineered barriers such as containers or solidification in matrices to contain the materials. Despite the fact that some engineered structures have survived intact through the ages, others, even if comparably designed, have not. The

key consideration for radioactive wastes is to assure environmental and public health protection. In this light, engineered barriers generally can be considered only as interim measures for containment. The physical, radiological, and chemical characteristics of the waste largely determine the balance between the degree to which engineered or natural barriers are used. For example, where natural barriers with superior containment characteristics are available, the requirements for engineered barriers may be reduced.

The type of containment utilized for storage or disposal should provide isolation consistent with the characteristics and hazard potential of the waste. With the basic safety requirements met, other factors, including cost and engineering convenience, become important. In general, however, disposal methodologies for radioactive wastes should rely primarily on containment by environmental barriers, especially if long term isolation needs to be provided. In choosing such environmental media it is important to select those that will reduce to the greatest extent possible the effect of potential interaction of the wastes with water, since water transport is probably the major pathway for long term exposure of humans.

Control Requirements

The use of controls is basic to reducing potential risk of acute and chronic exposures from radioactive wastes to a degree that they would be acceptable to society for both short and long time periods. A range of institutional, engineered, and natural barrier controls can be used to isolate radioactive waste materials from humans, depending on their nature and form. Such controls should be applied either singly or

in combination with a goal of obtaining total isolation of the wastes from the biosphere over their hazardous lifetime. When institutional control is the method chosen to provide environmental protection, no restrictions should be required on customary uses of associated land areas and surface and ground waters after 100 years; for radioactive wastes that would require protection beyond 100 years, as many physical and natural barriers as is practicable should be used to minimize environmental impact if one or more fails or is accidentally or intentionally breached. Also, environmental isolation media should be selected that reduce the effect of potential interaction with water to the greatest extent possible and for which natural forces such as erosion, sedimentation, and crystallization will enhance, rather than reduce, environmental isolation.

RISK PERSPECTIVES

The term risk expresses a general concept encompassing both the probability of occurrence of adverse effects and their severity (ICRP, 1977; Otway & Pahner, 1976) The concept may be used (Lowrance, 1976) as a measure of the degree of safety. Since it is often not possible to eliminate all risk associated with an otherwise beneficial activity, a judgment of "how safe is safe enough", under the circumstances, must be made. This is equivalent to deciding on a level above which the risk is unacceptable.

A society that is dependent on high technology necessarily abandons the concept of zero risk (Lapp, 1973). Individuals, consciously or unconsciously, make daily choices on a voluntary (or at least perceived to be voluntary) basis which lead to the acceptance of risks: how fast to drive, how much to smoke, whether or not to remain overweight, and so on. Governments have been delegated authority to allow levels of involuntary risks in the form of standards and regulations. Allowance of involuntary risks by government decisions requires that the considerations and assumptions upon which they are based be part of the public record. This section discusses factors basic to such determinations for radioactive wastes.

Radiation effects on health at low doses and dose rates are presumed to have a linear dose-response relationship for public health protection purposes. This implies that any radiation dose, however small, conveys a proportionate chance of producing a genetic alteration or a somatic health effect such as cancer. Neither of these effects is

certain to occur in an individual exposed below acute levels, and genetic effects in any case can materialize only in progeny. Within this context, therefore, the appropriate goal is to avoid any increment of radiation in the general environment due to radioactive waste. Because total avoidance of exposure may be very costly or difficult to guarantee, people might choose to forego the benefits of the waste-producing activities. Therefore, it is desirable to establish some guidelines to determine, when and if it appears to be necessary, levels of risk other than zero that may be permitted.

Methods for Examining Risks

There is no established rigorous procedure to determine levels of risk that society would accept for a given activity or enterprise (Otway, 1977). Several approaches have been proposed, however, as either complete or partial bases for regulatory actions. Although none of these methods provides all the elements that should be present in such a basis, the following discussion shows that a framework for decision-making can be established to which elements of each method may contribute some insight.

It has been suggested (Starr, 1969, 1972), for example, that analysis of risk acceptance experiences could lead to the establishment of relationships between risk and associated benefits for broad categories of societal activities. A regulatory body could then classify the nature of a particular hazard, and use the relations to guide a determination of the corresponding acceptable level of risk. The method has a technical weakness, in that the postulated relationships appear to be very difficult to develop from the available

data (Otway, Cohen, 1975). Perhaps of greater significance is the inherent deficiency that, even if these relations were quantitatively well determined, they would not describe optimal decisions, but only circumstantial ones. A further problem arises in applying the method to radioactive wastes because of the long-term persistence of the potential hazards they present, which implies that most of the people potentially at risk are not yet born. Current and future attitudes towards risks may differ significantly from those of even the recent past, especially for a technologic situation such as that of radioactive waste, whose impact on public consciousness has been growing. It is clear, then, that considerable caution is warranted when attempting to apply past experiences with other hazards to the determination of current and future levels of risks associated with radioactive wastes.

Another potential guide to the determination of levels of risks to be restricted is comparison with the involuntary risks due to exposure to the natural radiation background. It has been concluded that "...exposure to manmade radiation below the level of background radiation will produce additional effects that are less in quantity and no different in kind from those which man has experienced and has been able to tolerate throughout his history" (BEIR, 1972). This finding refers explicitly to genetic risks to a population and may be less applicable to somatic injuries to individuals. Acceptance of the linear nonthreshold hypothesis means that there can be no logical permissible lower limit based on dose alone.

Also, comparisons of risks associated with radioactive waste to more commonly understood societal risks can have considerable

communication value, but are of very limited usefulness as a determinant of permissible risk levels. For the reasons discussed above, and others, it is not clear that risk-benefit relations for past experience with other activities are necessarily pertinent to radioactive wastes. Therefore, even if such relations were quantitatively well determined, the logical basis for their applicability to this specific purpose would remain to be established.

An alternate approach which could guide the determination of acceptable levels of risk involves a variety of methods of assessing the attitudes and opinions of the general public. The participants at the EPA workshop defined "general public" to mean all members of society except those government officials with responsibilities regarding radioactive waste. Methods of assessment are the formal sampling and analysis procedures of sociology and psychology, which are designed to elucidate the opinions or the attitudes of representative population samples, or the less formal ones of opinion gathering in public forum, and by examination of available literature.

Utilizing psychometric techniques based on responses to questionnaires has only recently been applied to the problem of determining acceptable levels of risk, and is not yet available as an established procedure. Clearly, to be most useful to the determination of policy, such studies of attitude and opinion should satisfy high standards of fairness of execution and be representative of the entire society. Even if a definitive study of people's expressed preferences were done, it could serve as an adequate guide to regulatory action only if present opinions were accepted as a basis for decision. However,

people do not consistently act in accordance with their expressed preferences. Another problem is that planning guidelines logically would have to change with changes in public opinion, possibly resulting in social chaos (Slovic, 1976). Deciding relatively narrow issues, such as the acceptability of levels of risk for waste management systems, by public referendum as has been suggested (EPA, 1977b) suffers from the same serious deficiency and has severe problems of implementation.

If polling and psychometric techniques are incapable of providing the basis for environmental protection standards, they nevertheless offer helpful insight into the elements of risk that most significantly affect public acceptability. Attitude measurements are also capable of revealing differences in perception among groups of respondents. For example, commenting on a study of attitudes and values with regard to nuclear waste (Maynard, et al., 1976), one analyst found "...fairly consistent evidence that respondents who are representative of planners and decision makers differ considerably on many key issues from respondents who were more representative of the general public" (Slovic, 1976).

It could of course be argued that planners and decision makers are better informed than the general public, on the average, and could thus be expected to have differing views. However, when the differences concern basic attitudes and values, the decision makers should be especially careful and deliberate to assure that they receive and give full consideration to all points of view. Although no simple prescription for achieving this can be specified, open and timely opportunities for public participation in the decision-making process

would play a beneficial role, particularly at early stages (Campbell, 1976, Kuhlman, 1976).

The above discussion indicates that determining levels of risk that may be acceptable to society due to radioactive waste could not be accomplished with current methodologies solely by:

1. reference to past risk and benefit relations for activities and situations not related to radioactive wastes;

2. comparisons with risk due to the natural radiation background or commonly understood risks not related to radiation; or

3. assessment of public attitudes and opinions.

The absence of any single completely satisfactory procedure has not and should not prevent effective regulation of radiation exposure. Thus a framework for decision-making has evolved, in which the circumstances corresponding to each source of exposure are examined, and guidelines and regulations then developed which are intended to assure that any allowed exposures are reasonable, under the circumstances. The guiding principles of this approach to radiation protection are: a) that any allowed exposures or releases of radioactive material be associated with some justifying benefit, b) that exposures be kept as low as is reasonable in view of technical, economic, and social considerations, c) the inequitable distribution of risks among individuals in a given population should be minimized, and d) that certain stated levels of exposures of the general population are not to be exceeded, virtually without regard to circumstances. These general principles are subscribed to by Federal entities with responsibility in this area (EPA

1976b) as well as by the major quasi-official advisory bodies on radiation protection.

Attitudes Toward Assumption of Risks

Humans, by their nature, are risk-aversive, i.e. they normally seek to minimize risks unless the assumption of increased risk is compensated for by apparent benefits, or it is so low they do not particularly care about it. It is clear as well that the bearer's evaluation of risk, and hence its acceptability, varies according to factors other than the quantitatively expressed consequences and their probability of occurrence. These factors and their evaluation may also be significant elements of regulatory decisions for radioactive wastes, and may provide a social or psychological basis for accepting different levels of risk for wastes having different risk characteristics, even apart from technical or economic considerations.

Many authors have discussed these risk evaluation factors (Lowrance; Rowe; Otway), but only very preliminary attempts to associate numerical weights to them have been undertaken, and these efforts are yet controversial. Broadly speaking, however, risks appear to be more acceptable if: they are assumed voluntarily; the effects are delayed rather than prompt; they are not easily avoidable; the consequences are common ones and not highly dreaded, or are reversible; they are equitably distributed; and if the risk-taker is confident that the situation is well understood. Risks of comparable magnitude may be far less willingly assumed if they are associated with other characteristics. Therefore, when the adequacy of a given level of control of a particular form of radioactive waste is being evaluated, it

is appropriate to consider both quantitative and qualitative characteristics of the risk. As with other aspects of the regulatory process, however, the scope of the considerations and the bases for decisions should be fully documented.

Risks for Naturally Radioactive Wastes

Radioactive wastes containing naturally occurring radioactivity are materials which all people encounter in nature to varying degrees, and for which average doses as components of natural background radiation are known. The excavation and processing of the materials makes them more accessible to humans, but even in the undisturbed state they contribute some level of radioactivity to the general environment. Since the parent isotopes of much of this natural radioactivity have half-lives of billions of years, natural processes such as erosion, leaching, glaciation, and tectonism might ultimately release into the biosphere most of those naturally occurring radionuclides currently trapped in the earth's crust. It is therefore not clear whether mining them has any effect other than releasing them to the biosphere sooner and more surely. Whatever the natural state may be, it is reasonable to suppose it to be stable enough to assure against substantial increases in the level of background radiation due to naturally occurring radionuclides for some thousands of years. A condition for acceptability of the control of such materials as wastes would be to prevent individual or population exposures in excess of background levels which already exist at the undisturbed site.

For time periods considerably longer than thousands of years, requirements for these naturally occurring materials are less obvious,

since natural processes would be expected to release the radioactivity eventually. Therefore, while considerable efforts are justified in attempting to provide protection for much longer than thousands of years, a disposal method for naturally-radioactive wastes which does not appear capable of achieving this will not necessarily be unacceptable.

Naturally-radioactive wastes which are substantially modified from their natural state, such as discarded radium sources, are essentially human-produced materials. The considerations discussed above are clearly not applicable to these materials.

Risks for Human-Produced Radioactive Waste

Setting long-term disposal objectives for human-produced wastes is especially problematic in view of the difficulty in accurately forecasting conditions and events far into the future. For virtually any means of disposal on earth, even though designed not to release the waste, there always will be a chance of failure over a very long time. It is therefore necessary to decide upon an allowable probability that a given set of consequences may occur as a result of radioactive waste disposal, even though these consequences may be unintended. Some useful perspectives on these long-term risks of chronic exposure may be gained through certain comparisons.

The first observation, in this regard, is that quantities of many of the same radionuclides present in such radioactive wastes have already been dispersed in the biosphere by explosions of nuclear weapons. Additional inventories of the same or comparable radionuclides are contributed by natural processes, i.e. those which occur without human intervention. Some appreciation of the long-term significance of

the potential effects of human-produced radioactive wastes may be gained by comparison of the concentrations of long-term radionuclides in air, soil, and water with concentrations due to other sources. In order to assure limitation of the consequences due to the waste, and to allow for continued use of radioactivity in the future, it is clearly desirable that these waste concentrations be small compared to those of the same or similarly hazardous nuclides which already exist. Furthermore, any eventual chronic radiation exposures to any organ of the body due to waste should be small compared to exposure due to natural background radiation.

These conclusions are proposed as necessary conditions to be satisfied even if attempts to isolate long-lived waste should fail over a very long period of time. Within these conditions, the levels of risk which are sufficiently low to be acceptable must be determined by examination of all the technical, economic, and social factors pertaining to a specific form and quantity of material.

Low Probability-High Consequence Events

A few kinds of radioactive wastes are capable of producing severe environmental and public health impacts on at least a regional scale if they were dispersed, such as large quantities of nuclear reactor fuel reprocessing wastes or the spent fuel itself. This potential hazard is intrinsic to the material although it generally declines with time in accordance with the laws of radioactive decay. So long as the radioactivity exists, however, the control system will be required to reduce to very low levels the probability of occurrence of high consequence events. For these potentially high consequence events, as

for others, the level of protection that should be considered adequate is still a controversial matter.

It has already been noted that there is no definitive basis for deciding acceptable levels of risk. For events with high consequences, however, it is possible to achieve useful perspectives on the waste management requirements by means of certain comparisons. The first observation is that, since the waste itself serves no useful purpose, its management system should provide greater security against a major disaster than is acceptable for dams, dikes, large stores of toxic or explosive chemicals, and other beneficial situations having high potential hazards. This provides reasonable guidance for a necessary constraint on radioactive waste, but it certainly does not define conditions which are sufficient.

A second useful observation is that, as a general rule, it will not be fruitful to attempt to reduce the probability of already highly improbable modes of disrupting waste which, if they occurred, would independently produce consequences hundreds of times greater than those attributable to the waste. This implies that undue consideration need not be devoted to designing against major disruptions of waste by massive meteorite impacts, nuclear war, ice ages, or comparable cataclysms. This condition provides guidance regarding a sufficient degree of protection, but only for a certain category of disruptions. In applying this condition, however, both the immediate and the long-term consequences of the released radioactivity should be considered. Since no mechanism can be prescribed for judging the adequate degree of protection against a disaster associated with radioactive waste, public

policy decisions should be guided by the perspectives and the necessary and sufficient conditions described above.

Perspectives for Restricting Risks

No prescription can be stated for judging an adequate degree of protection for radioactive wastes independent of circumstances. A number of conditions are generally regarded as basic to sound public health practice: a) any allowed exposures to or releases of radioactive materials should be associated with some justifying benefit; b) exposures should be kept as low as is reasonable to achieve in view of technical, economic, and social considerations; and c) inequitable distribution of risks among individuals in a given population should be minimized, and d) certain stated levels of exposures of the general population are not to be exceeded, virtually without regard to circumstances.

Naturally-radioactive wastes should be disposed of in a manner that will prevent for thousands of years individual or population radiation exposures in excess of those that natural processes might produce if the material had remained undisturbed by people. While considerable efforts may be justified to provide protection for much longer than thousands of years, a disposal method which appears incapable of achieving this will not necessarily be unacceptable. Disposal systems for human-produced radioactive wastes should isolate these materials from humans until their radioactivity has essentially disappeared. This may not be possible to achieve for very long-lived radionuclides.

Radioactive wastes should be provided greater security against major adverse consequences of failure than is acceptable for dams,

dikes, toxic chemicals, and other generally useful situations having high potential hazards. Little useful purpose would be served by undue consideration for protection of radioactive wastes against cataclysmic disruptions which, if they should occur, would have consequences greatly exceeding any that are attributable to the waste.

OTHER CONSIDERATIONS FOR RADIOACTIVE WASTE

A number of other subjects pertinent to protection of the public from radioactive wastes were discussed in the EPA workshops. Three subjects that received a good deal of attention were considerations for monitoring, retrievability, and passive communication of the nature of the hazard to future generations that could be impacted. In general, it was determined that, while each is desirable in the conventional sense for dealing with radiological hazards, their application might undermine the goal of providing permanent isolation for wastes. It is difficult to maintain retrievability or conduct a monitoring program without compromising the ability to provide isolation; communication, even though of value, cannot appropriately be depended on as a form of control. Nonetheless, each may, in certain cases, enhance overall protection from wastes, and in such cases it would be prudent to use them.

Monitoring

During the operational phase of a waste facility, offsite monitoring of environmental radiation may be required in order to:

a. extend knowledge of baselines of radiation in the general environment near the facility

b. verify that any effects produced by releases from the site by any pathways are and may be expected to remain within acceptable levels

c. provide information in the event of unanticipated releases which will be useful in assessing the extent of environmental contamination and will allow for timely consideration of remedies.

The nature and extent of offsite environmental monitoring during operation of a waste facility would depend on the form and potential hazard of the waste material, the character of the operations performed upon them, the types of containment barriers used, and the mechanisms by which these barriers might be breached. However, all waste facilities should be designed in such a manner that monitoring for more than 100 years would not be required as a basic element of environmental protection.

Retrievability

A waste management system provides for retrievability of the waste if it incorporates a designed provision for recovery of the waste materials. The necessity of such a feature is obvious for any phase of the management system prior to disposal.

The principal reasons in favor of retrievable waste management systems are:

a. They offer an opportunity for correction of unanticipated failures of the isolation methodology.

b. They may allow future societies the prerogative of applying advanced knowledge to improve upon earlier efforts in waste disposal.

c. They permit recovery of the waste as a resource, if uses for it should develop in the future.

The disadvantage of retrievability is that it necessarily increases the probability that the waste will not remain isolated from humans. Systems with designed provisions for recovery of the radioactive

materials in general cannot be as secure from intrusion as those which lack such features.

It should be recognized that the incorporation of retrievability itself injects a degree of uncertainty since it increases accessibility. In justifying its application, a tradeoff of these uncertainties is necessary, with the maintenance of an acceptable level of safety remaining the major consideration. Although conclusions regarding the desirability of a retrievable design may vary with the features of individual disposal systems, certain general considerations apply to all cases. The most important of these is the effect that provisions for retrieval would have on the integrity, and thereby the safety, of an otherwise adequate disposal technology. For example, access tunnels (however sealed) and monitoring probes within an underground disposal site would, to a certain extent, compromise the integrity of the natural barriers. If retrievability is to be justified, this lessened degree of safety should be compensated for by other advantages. One case where retrievability may well be justified as enhancing protection is the packaging of materials for near surface disposal so they may be exhumed early if circumstances make such action desirable. In this case, the packaging would not be expected to make the materials more available for environmental release.

It would appear that, in general, retrievable disposal systems should be avoided. However, the possibility remains that the characteristics of some particular waste and its disposal technology may be such that retrievability would be judged to offer a net advantage.

Future Identification

A means of disposal may satisfy the environmental and public health protection criteria, but the possibility may remain that, after the period during which institutional controls can be relied on, an accidental or intentional disturbance of the disposed materials could present a hazardous situation to an individual or a population. Where this possibility exists, it may be determined that such disturbances may be prevented by the use of passive means of communicating the nature of the hazard to future people. The efficacy of this approach should be evaluated for each source and its corresponding disposal circumstances.

SUMMARY AND RECOMMENDATIONS

Although most waste materials contain some radioactivity, their designation as radioactive wastes is dependent on their having no perceived value, their origin, and whether the materials pose undesirable exposure circumstances. Radioactive wastes can for the most part be grouped into two broad categories: discrete sources of human-produced and naturally-occurring radioactive materials, and diffuse naturally-occurring radioactive materials such as mining residues. Included in this characterization are all radionuclides retained because of regulatory restrictions on their release to the environment.

The overriding consideration for establishing a level of control required for the storage and disposal of radioactive wastes involves judgments on the amount and rate of exposure to humans and environmental contamination that are to be accepted. An essential element of such judgments is the estimation of health effects which would result from acute and chronic exposure of individuals and populations at various levels of possible control, recognizing the various types, forms, and physical characteristics of wastes. Although controlling the potential impact on humans is essential, it is in itself not a totally sufficient condition because of the trustee responsibility each generation has to succeeding ones. For this reason, it is also essential to prevent any unnecessary contamination of the environment which is reasonably achievable even though human interactions with the wastes in concentrated form could not be presently predicted. From these

considerations, the goal for control of radioactive wastes should be to prevent its introduction into the biosphere over its hazardous lifetime.

Predictions of risks are uncertain due to a number of factors. For practical purposes such determinations would not generally be dependable, informative, and therefore not very useful for time periods extending much beyond 1000 years, although certain general considerations may be useful for certain radionuclides beyond this period. Decisions on the levels of risk to be controlled are dependent, however, on such determinations and on a range of technical, economic, and social considerations. Radiation protection policies need to reflect this framework of factors; the type and degree of controls will be determined accordingly.

The long-term nature of some radioactive wastes requires decisions on risk transference and the extent to which institutions may be depended upon to provide public health and environmental protection. Although it is a desirable goal to insure that risks to future generations will be no more than those to present generations due to the persistence of the waste, it is questionable whether current techniques can provide this assurance. It is obvious, however, that unplanned events resulting in population exposure are more probable subsequent to lapse of institutional care by virtue of eventual degradation of the barriers which provide isolation through natural and, possibly, human activities. It would therefore be reasonable, in the face of these uncertainties, to recommend equity of risk transference as a goal to be achieved. There are practical limitations to relying on institutions alone to provide the required control beyond about 100 years.

Therefore, environmental and public health protection for the storage and disposal of radioactive wastes involves a number of factors. Among these are: (1) a clear distinction of which radioactive materials are properly considered to be radioactive wastes, (2) assessment of the potential health risk of the various wastes over appropriate time periods representative of their possible impact and concern for future generations, (3) the long-term implications and the persistence of risk in determining the ability of institutions to maintain protection of both humans and the general environment, (4) isolation of the waste by the application of engineering controls and environmental barriers to minimize probability of re-entry to the environment within time periods of concern, (5) considerations of risks at a given level of control and their acceptability, and (6) other considerations for operational controls, retrievability, monitoring, and the transfer of information to succeeding generations to aid in providing environmental protection.

Initial Formulations of Criteria

The considerations presented above have been addressed by the EPA in order to arrive at an initial formulation of criteria for public review and discussion. These formulations, which are yet to be proposed in formal language in the Federal Register, are believed to represent the major areas for which criteria are indicated and the substance of the criteria that will be issued. Following response to these initial criteria by the public, they will be formally proposed as guides for developing standards to protect the environment and the public due to the storage and disposal of radioactive wastes.

Initial formulations of criteria for waste materials, risks and their acceptability, and controls are recommended as follows:

Radioactive Waste Materials

1. Radioactive material which has no designated resource or product value should be considered radioactive waste requiring environmental protection if it: a) is produced by nuclear fission or activation, b) contains naturally-occurring radioactive material that if disposed into the biosphere would increase exposure above that normally occurring in pathways due to the natural state of the area, or c) is restricted from routine release to the biosphere; examples* of such radioactive waste materials that should be subject to environmental protection requirements are:

- All radioactive materials associated with the operation and decommissioning of nuclear reactors for either military or other purposes and the supporting fuel cycles, including spent fuel, fuel reprocessing wastes, and radionuclides removed from effluents.
- Artificially produced radioisotopes for medical, industrial, and research use, including discrete radium sources, and waste materials contaminated with them.
- The naturally radioactive residues of uranium and phosphate ore recovery and associated milling and conversion operations.

*The Agency has determined that the materials listed should be subject to environmental protection criteria even though some such materials may not upon examination require any control above that they would receive as ordinary wastes; other radioactive materials may also be included if they are found to satisfy similar considerations.

Risk and Risk Acceptability

2. Environmental protection determinations for radioactive wastes should be based primarily on an assessment of risk to individuals and populations; such assessments should be based on examination of at least the following factors:

a. The total amount of radioactive waste in a location and its persistence due to its physical form and the lifetime and concentration of the radicnuclides contained in the wastes;

b. The potential adverse health effects on human individuals and populations for a reasonable range of future population sizes and distributions and uses of land, air, water, and mineral resources for one thousand years, and general estimates of adverse effects for longer periods for materials having potential impact beyond one thousand years when such estimations could determine the selection of a more effective disposal option.

c. The projected effectiveness of alternative methods of institutional, engineered, and natural barrier controls used singly or in combination; and,

d. The probabilities of releases of radioactive materials to the general environment due to disruption of the waste through failures of natural or engineered barriers, loss of institutional controls, or intrusion; and

e. The uncertainties in the risk assessments and the models used for their determination.

3. Risks due to radioactive waste should be deemed unacceptable unless it is justified that more complete isolation of such wastes is unreasonable in view of technical, economic, and social considerations; any potential risks to a future generation should be no greater than those accepted by the current generation. Any potential risk for radioactive waste storage or disposal at a particular level of control should be considered unacceptable if:

a. any exposure having a high probability of occurrence could result in more than a chronic risk which could not be further reduced by reasonable controls,

b. the levels of any chronic risks are not less than those for comparable high probability circumstances acceptable to society, or

c. high consequence events do not have a probability of occurrence less than that for comparable high consequence events accepted by society for similar productive technologies.

Control of Radioactive Waste

4. Controls should be applied with a goal of isolating radioactive wastes from the biosphere over their hazardous lifetime to protect humans and minimize unnecessary contamination of the environment. When institutional control is the method chosen to provide environmental protection of radioactive wastes, no restrictions on customary uses of associated land areas and surface and ground waters due to any residual risks should be required after 100 years; radioactive wastes that would require protection beyond 100 years should not be isolated by

institutional means, but rather by as many physical and natural barriers as is practicable to minimize environmental impact if one or more fails or is accidentally or intentionally breached.

5. Locations for radioactive waste disposal should be chosen whenever practicable such that the action over time of natural forces such as erosion, sedimentation, and crystallization could be projected to improve, rather than reduce, environmental isolation; if used to isolate wastes, geological media should reduce the effect of potential interaction of the waste with water to the greatest extent possible.

6. Certain additional procedures and techniques should also be applied to waste disposal systems which otherwise satisfy these criteria if they provide a net improvement in environmental and public health protection; among these are:

a. monitoring prior to completion of disposal to determine for timely correction any unanticipated effects which could result in releases of radioactivity to the general environment,

b. procedures or techniques designed to enhance the retrievability of the waste, and

c. passive methods of communicating to future people the potential hazards which could result from an accidental or intentional disturbance of radioactive wastes.

GLOSSARY

barrier - any medium which stops or significantly retards the movement of emplaced radioactive materials

engineered barrier - a barrier of human manufacture, such as a container or solidified waste matrix

natural barrier - a barrier consisting of a geological or other natural medium

disposal of radioactive waste - the placement of radioactive waste with no intent of recovery

facility, waste management - the structure and/or the location at which some waste management activity is performed or occurs

general environment - the total terrestrial, atmospheric, and aquatic environments outside sites upon which any radioactive waste management activity is conducted (see also; site, waste management)

institutional controls - activities, devices, combinations of each which involve the performance of functions by human beings to limit contact between the waste and the human environment

isolation, radioactive waste - the placement of radioactive waste such that contact between the waste and the human environment will be highly unlikely for a chosen period of time

monitoring - a program to measure the quantity and type of discharges or releases from a waste management facility or to measure changes in physical, chemical, or biological characteristics of the site and its surrounding region

retrievability - a designed capability to recover waste from an emplaced location, whether temporary or permanent

risk - a general concept encompassing the probability and the severity of adverse effects

site, waste management - any location that is contained within a boundary across which transit by the members of the general public is controlled because of the operation or presence of a waste management facility

storage, radioactive waste - retention of radioactive waste at facilities with designed provisions for recovery

waste management - a generic term describing the range of activities for dealing with radioactive waste, including preparation, storage, and disposal

APPENDIX A

Summary of Workshop Findings

Issues pertaining to the establishment of these criteria were discussed in two informal workshops held by EPA in Reston, Virginia (February 3-5, 1977) and Albuquerque, New Mexico (April 12-14, 1977). While discussion of various problems inherent in radioactive waste management elicited a diversity of responses from the workshop participants, a general consensus was reached in many areas. In formulating the initial criteria in this Background Report, EPA took into account the major items recommended by the Workshops which can be summarized as follows:

1. Radioactive waste criteria should not address disposal of high-level wastes alone but should also address other types of radioactive wastes and other methods of waste management such as storage of wastes. In particular, clear definitions should exist for radioactive wastes and waste management.

2. Participants in the Reston Workshop felt that criteria may have to be categorized based on such factors as concentration, relative hazard, and the waste form and/or disposal techniques; however, discussion at the Albuquerque Workshop raised doubts concerning the feasibility of this approach, due to the disparate characteristics of the various waste types. It was generally concluded by both Workshops that it is desirable for the criteria to address radiation exposure,

regardless of its source, which may preclude the necessity of distinguishing between waste types.

3. It was generally agreed at the Albuquerque Workshop that both maximum individual dose and population dose limitations should be considered, and that natural background radiation levels are the appropriate lower limit below which efforts to decontaminate an area would not be justifiable.

4. Concerning risk acceptability, participants in both workshops felt strongly that the criteria should be based on a consideration of risk and its acceptability, and that, while calculated risk is important, perceived risk must also be taken into account. Some participants felt that risks associated with radioactive wastes should be placed in the context of other risks from similar pollutants or environmental hazards. The intention here would be not to relax controls of radioactive waste but to improve the controls of other environmental hazards.

5. Considerable discussion about the concept of "zero" release and "zero" dose took place at Reston. Some participants felt these goals to be very desirable. Others felt strongly that zero should not appear in a criterion or standard since it is impossible to attain. Most participants felt that criteria should specify levels of control which isolate wastes from the biosphere for the period of concern.

6. Many participants in both workshops supported the premise that wastes be managed such that risks to future generations be no greater than the present generation is willing to accept for itself. The majority of the Reston participants believed that cost is of secondary

importance to safety although the economic aspect should not be ignored. Many felt that, in considering long-term safety, an unending time period should be employed. Some participants in Albuquerque emphasized that since this generation has little control over the stability of future societal institutions, the criteria should address a specified future time.

7. A consensus was reached at Albuquerque that all unplanned events and accidents should be considered by EPA in developing criteria and setting standards. No consensus was reached, however, on how this consideration should be addressed.

8. A clear consensus was voiced at Reston that isolation of high-level radwastes in suitable geological formations is desirable. Monitoring should be performed and assumptions on isolation and storage techniques should be checked while the site receives waste. While the Albuquerque participants felt that bases for retrievability existed, this option should only be considered when safety will not be compromised.

REFERENCES

(AEC, 1975) Atomic Energy Commission, The Nuclear Industry - 1974, Report: WASH-1174-74 (1975)

(BEIR, 1972) The Effects on Populations of Exposure to Low Levels of Ionizing Radiation, National Academy of Sciences - National Research Council (BEIR Report) (1972)

(Campbell, 1976) Campbell, A.K., Statement in Proceedings of Conference on Public Policy Issues in Nuclear Waste Management, Chicago (October 27-29, 1976)

(Cohen, 1972) Cohen, J.J. et al., In Situ Incorporation of Nuclear Waste in Deep Molten Silicate Rock, Nuclear Technology 13: 76 (1972)

(EPA, 1976a) Swift, J.S. et al., Potential Radiological Impact of Airborne Releases and Direct Gamma Radiation to Individuals Living Near Inactive Uranium Mill Tailings Piles, Report: EPA-520/1-76-001 (January 1976)

(EPA, 1976b) U.S.E.P.A., Program Statement, Report: EPA-520/7-76-007 (May 1976)

(EPA, 1977a) U.S.E.P.A., Proceedings: A Workshop on Policy and Technical Issues Pertinent to the Development of Environmental Protection Criteria for Radioactive Wastes, Report:ORP/CSD-77-1, Reston, VA (1977)

(EPA, 1977b) U.S.E.P.A., Proceedings: A Workshop on Policy and Technical Issues Pertinent to the Development of Environmental Protection Criteria for Radioactive Wastes, Report: ORP/CSD-77-2, Albuquerque, NM (1977)

(EPRI, 1976) Dan, G.J. and R.F. Williams, Status of Commercial Nuclear High-Level Waste Disposal, Electric Power Research Institute Report: EPRI-NP-44-SR (September 1976)

(ERDA, 1976) U.S.E.R.D.A., LWR Spent Fuel Disposition Capabilities, 1976-1985, Report:ERDA-76-25 (May 1976)

(FRC, 1960) Background Material for the Development of Radiation Protection Standards, Federal Radiation Council Report No. 1, May 1960; Radiation Protection Guidance for Federal Agencies, Federal Register :4402-4403 (May 18, 1960)

(GAO, 1976) General Accounting Office, Improvements Needed in the Land Disposal of Radioactive Wastes - A Problem of Centuries, Report: RED 76-54, Series B-164105 (January 12, 1976)

(Hendricks, 1977) Hendricks, D.W., Uranium Mill Tailings Storage, Use and Disposal Problems, Presented at University of Nevada Conference on Uranium Mining Technology, Reno, Nevada (April 28, 1977)

(Holcomb, 1978) Holcomb, W.F., A Summary of Shallow Land Burial of Radioactive Waste Commercial Sites Between 1962 and 1976, with Projections, Nuclear Safety 19, No. 1 (January/February 1978)

(ICRP, 1977) Recommendations of the International Commission on Radiological Protection, ICRP Publication No. 26, Pergamon Press (January 1977)

(JCAE, 1975) Storage and Disposal of Radioactive Wastes, Hearing Before Joint Committee on Atomic Energy, the United States Congress, U.S. Government Printing Office, (November 19, 1975)

(Kuhlman, 1976) Kuhlman, C.W., Statement in Proceedings of Conference on Public Policy Issues in Nuclear Waste Management, Chicago (October 27-29, 1976)

(Lapp, 1973) Lapp, Ralph, Aware, No. 39 (December 3, 1973)

(Lowrance, 1976) Lowrance, W.W., Of Acceptable Risk: Science and the Determination of Safety, William Kaufmann, Inc., Los Altos, California (1976)

(Maynard, 1976) Maynard et al., Public Values Associated with Nuclear Waste Disposal, Battelle Memorial Institute, Report BNWL-1997, (June 1976)

(NAS, 1976) The Shallow Land Burial of Low-Level Radioactively Contaminated Solid Waste, National Academy of Sciences - National Research Council, Report No. TID-27341 (1976)

(NRC, 1976) U.S. Nuclear Regulatory Commission, Alternative Processes for Managing Existing Commercial High-Level Radiaoctive Wastes, Report: NUREG-0043 (April 1976)

(O'Connell, 1974) O'Connell, M.F. and W.F. Holcomb, A Summary Of Low-Level Radioactive Waste Burial at Commercial Sites Between 1962 and 1973, With Projections to Year 2000, Radiation Data and Reports 15, No. 12, (December 1974)

(Otway, 1977) Otway, H.J., A Review of Research on the Identification of Factors Influencing the Social Response to Technological Risks, International Atomic Energy Agency, Report: IAEA-CN-36/4

(Otway and Cohen, 1975) Otway, H.J. and Cohen, J.J., Revealed Preferences: Comments on the Starr Benefit - Risk Relationships, International Institute for Applied Systems Analysis, Report: RM-75-5 (March 1975)

(Otway and Pahner, 1976) Otway, H.J. and P.D. Pahner; Risk Assessment, Futures (April 1976)

(Rochlin, 1977a) Rochlin, G.I., Nuclear Waste Disposal: Two Social Criteria, Science (January 7, 1977)

(Rochlin, 1977b) Rochlin, A.I., Long-Term Waste Management: Criteira or Standards? Paper in Proceedings: A Workshop on Issues Pertinent to the Development of Environmental Protection Criteria for Radioactive Wastes, EPA Report ORP/CSD-77-1 (1977)

(Rowe, 1977) Rowe, W.D., An Anatomy of Risk, John Wiley and Sons, New York (1977)

(Schiager, 1977) Schiager, K.J., Radwaste Radium-Radon Risk, paper in Proceedings: A Workshop on Policy and Technical Issues Pertinent to the Development of Environmental Protection Criteria for Radioactive Wastes, EPA Report: ORP/CSD-77-2 (1977)

(Slovic, 1976) Slovic, Paul, Psychological Factors in the Perception and Acceptability of Risk: Implications for Nuclear Waste Management; paper prepared for Conference on Public Policy Issues in Nuclear Waste Management, Chicago (October 27-29, 1976)

(Starr, 1969) Starr, Chauncey, Social Benefit Versus Technological Risk, Science 166:1232 (March 19, 1969)

(Starr, 1972) Starr, Chauncey, Benefit - Cost Studies in Sociotechnical Systems, article in Perspectives on Benefit-Risk Decision Making, National Academy of Engineering (1972)

(10 CFR 20) Code of Federal Regulations, Title 10, Part 20, Standards for Protection Against Radiation (January 1975)

(Wong, 1973) Wong, D.T. and A.F. Kluk, Recent Improvements in the Management of Radioactive Solid Waste at AEC Nuclear Sites, presented at the AICHE 66th Annual Meeting, Philadelphia (November 11-15, 1973)